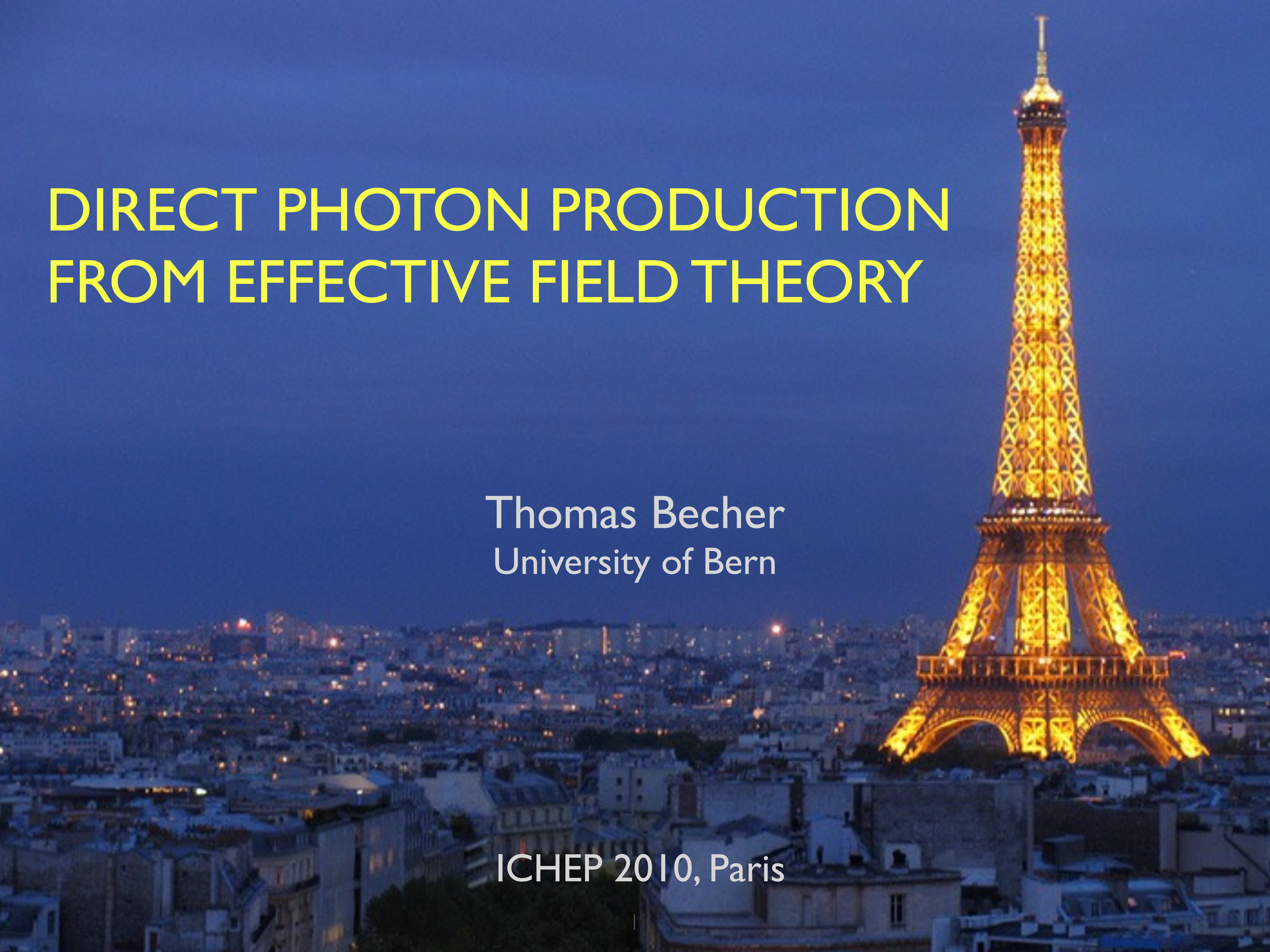

# DIRECT PHOTON PRODUCTION FROM EFFECTIVE FIELD THEORY

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# OUTLINE

- Introduction
  - Soft-Collinear Effective Theory
  - Photon production cross section
- NNLL resummation for at large $p_T$ photon production

  TB, M. Schwartz 0911.0681
  - Resummation by RG evolution
  - Numerical results and comparison to Tevatron data
- NNLL resummation for W and Z production

  TB, Ch. Lorentzen, M. Schwartz, to appear

# SOFT-COLLINEAR EFFECTIVE THEORY

Bauer, Pirjol, Stewart et al. 2001, 2002; Beneke et al. 2002

- EFTs split physics into high- and low-energy part. In collider processes, we have an *interplay of three momentum regions*
  - Hard } **high-energy**
  - Collinear
  - Soft } **low-energy part**
- Correspondingly, EFT for such processes has two low-energy modes:
  - Collinear fields describing the energetic partons propagating in a given direction, and
  - soft fields which mediate long range interactions among them.

# RESUMMATIONS WITH SCET

- EFT provides an elegant framework to factorize contributions associated with different scales.
  - Terms enhanced by large log's of scale ratios are resummed by RG evolution
- By now, many applications of SCET to collider processes. Resummations in many cases up to $N^3LL$:
  - thrust distribution in $e^+e^-$ — TB, Schwartz '08; Abbate et al. '10
  - Drell-Yan rapidity dist. — TB, Neubert, Xu '07
  - Drell-Yan, low $p_T$ — Gao, Li, Liu '05; Idilbi, Ji, Yuan '05; Petriello, Sonny '09; TB, Neubert to appear Monday
  - inclusive Higgs production — Idilbi, Ji, Ma and Yuan '06 ; Ahrens, TB, Neubert, Yang '08, update for ICHEP, see M. Neubert's talk
  - ...

all of these involve **two** directions of large energy flow

# N-JET PROCESSES

- Important progress in past year towards higher-log resummation of processes with large energy flow in several directions.
  - All-order constraints on the anomalous dimensions from soft-collinear factorization, factorization in collinear limit, non-abelian exponentiation.

    TB, Neubert '09; Gardi, Magnea '09 + Dixon '09
  - General result for hard anomalous dimensions relevant for NNLL of *n*-jet processes
    - massless: determined by constraints

      explains two-loop results of Aybat, Dixon and Sterman '06
    - massive: two-loop computation of three-particle correlations

      Ferroglia, Neubert, Pecjak, Yang '09

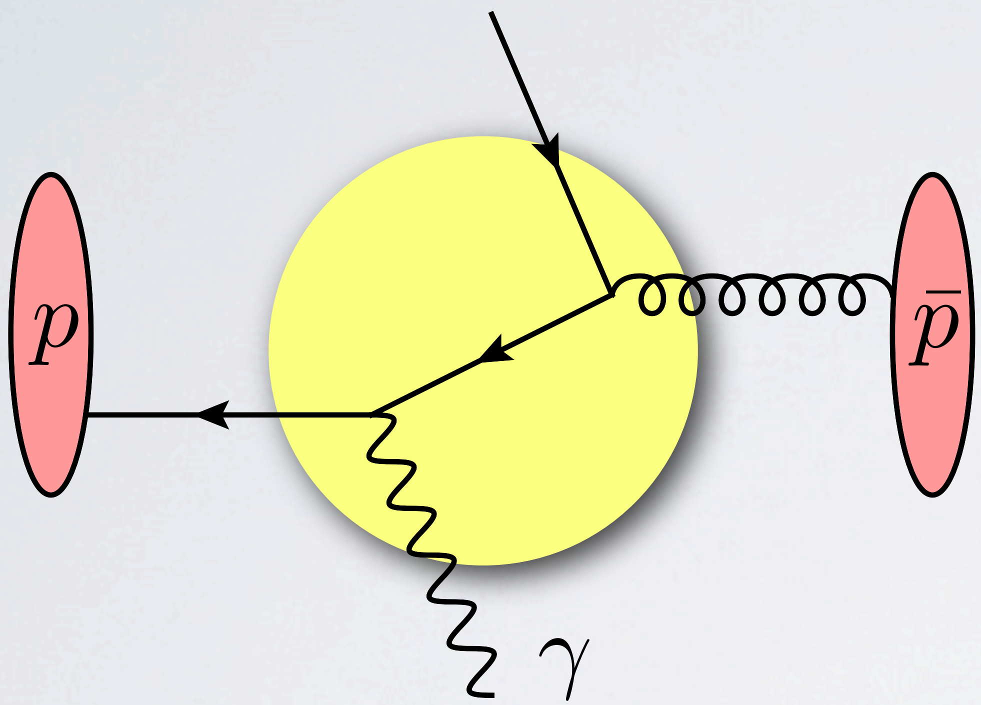
# PHOTON PRODUCTION $pp \to \gamma + X$ AT LARGE $p_T$

TB, M. Schwartz 0911.0681

- First SCET calculation of a physical cross section with energetic particles in three directions.
- Perform NNLL resummation of $\alpha_s^n \log^{2n}(M_X/p_T)$ corrections arising for at large $p_T$.
  - NLL was known Laenen et al. '98, Catani et al. '98, Kidonakis and Owens '99
- In the meantime we have extended the result also to $W^{\pm}$ and $Z$ production TB, Lorentzen, Schwartz, to appear
- Other examples involving multiple directions
  - top-production Ahrens, et al. '10
  - EW Sudakov resummation Chiu, et al. '08, '09

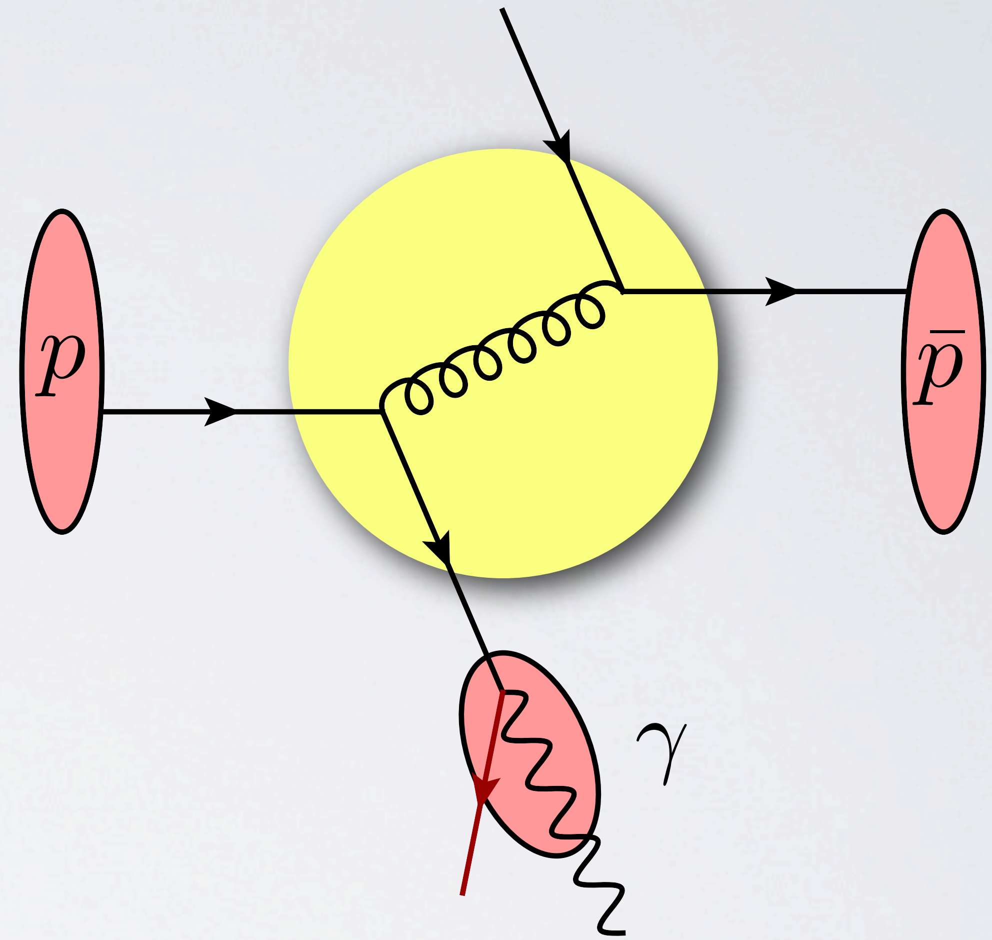
# PHOTON PRODUCTION MECHANISMS

- Direct production



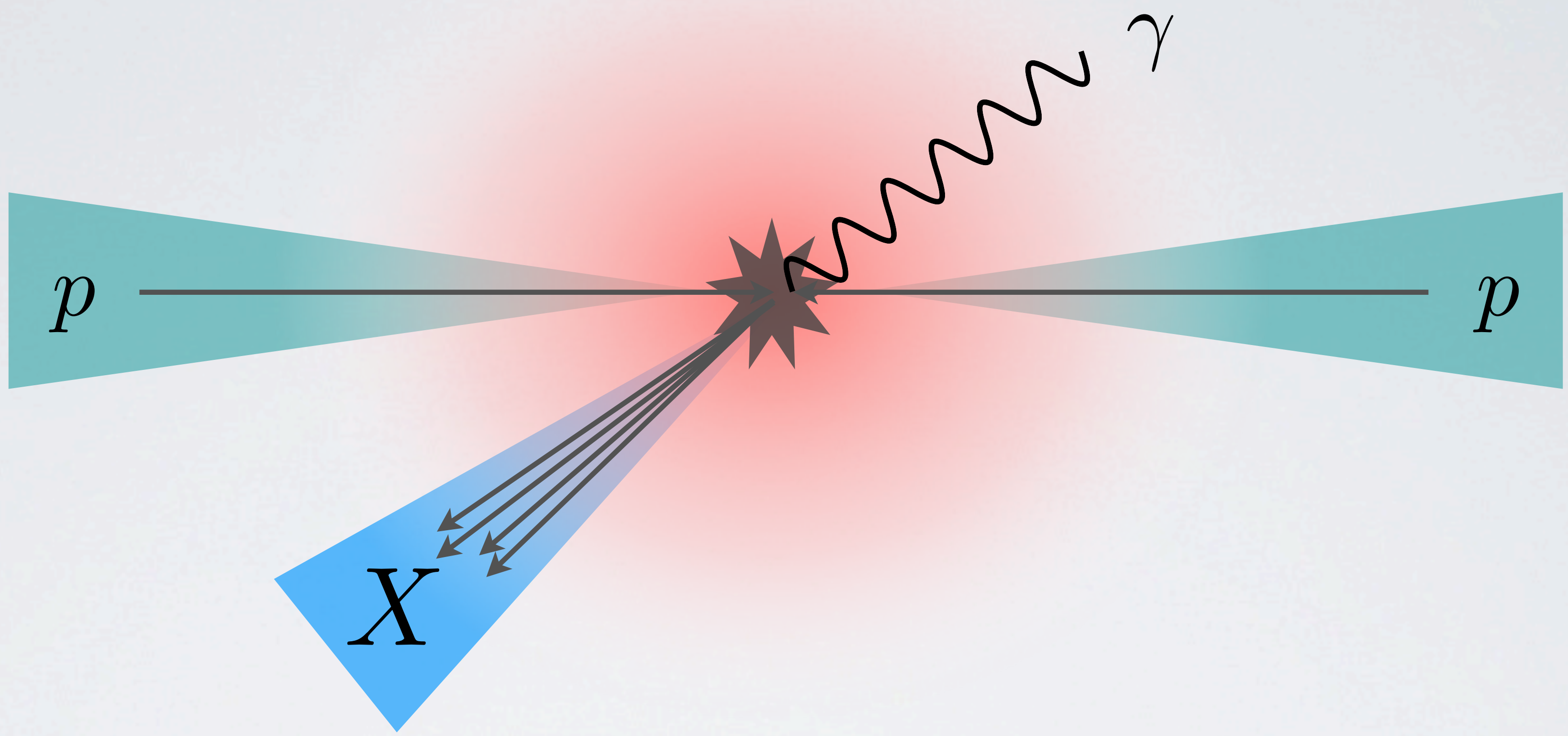

- sensitive to gluon PDF
- dominates fragmentation very at high $p_T$
- perform NNLL resummation for this part match to NLO (own code for inclusive case; JetPhox for isolation)

- Fragmentation




- needs non-perturbative fragmentation function
- can be suppressed by putting isolation cone around $\gamma$
- included in NLO (Jetphox)

# FACTORIZATION THEOREM AT LARGE $P_T$



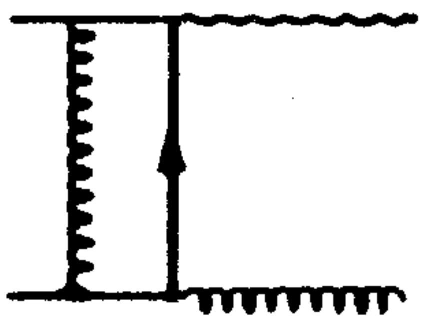

- Have derived factorization theorem for prompt photon production at large $p_T \gg M_X$

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}y\mathrm{d}p_T} = H \otimes J \otimes S \otimes f_1 \otimes f_2$$

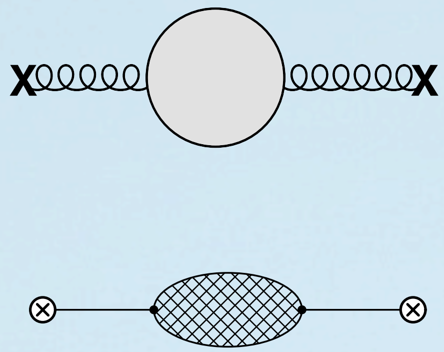
  - (there are different partonic channels, with different *H*, *J*, *S* and *f*'s)

# HARD, JET AND SOFT FUNCTIONS

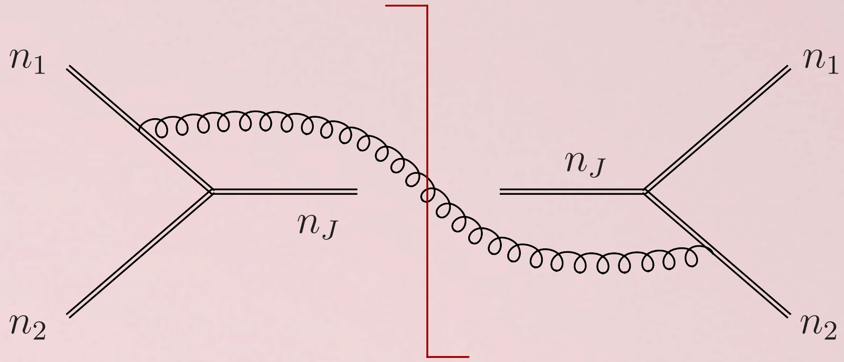
Hard function



Jet function



Soft function

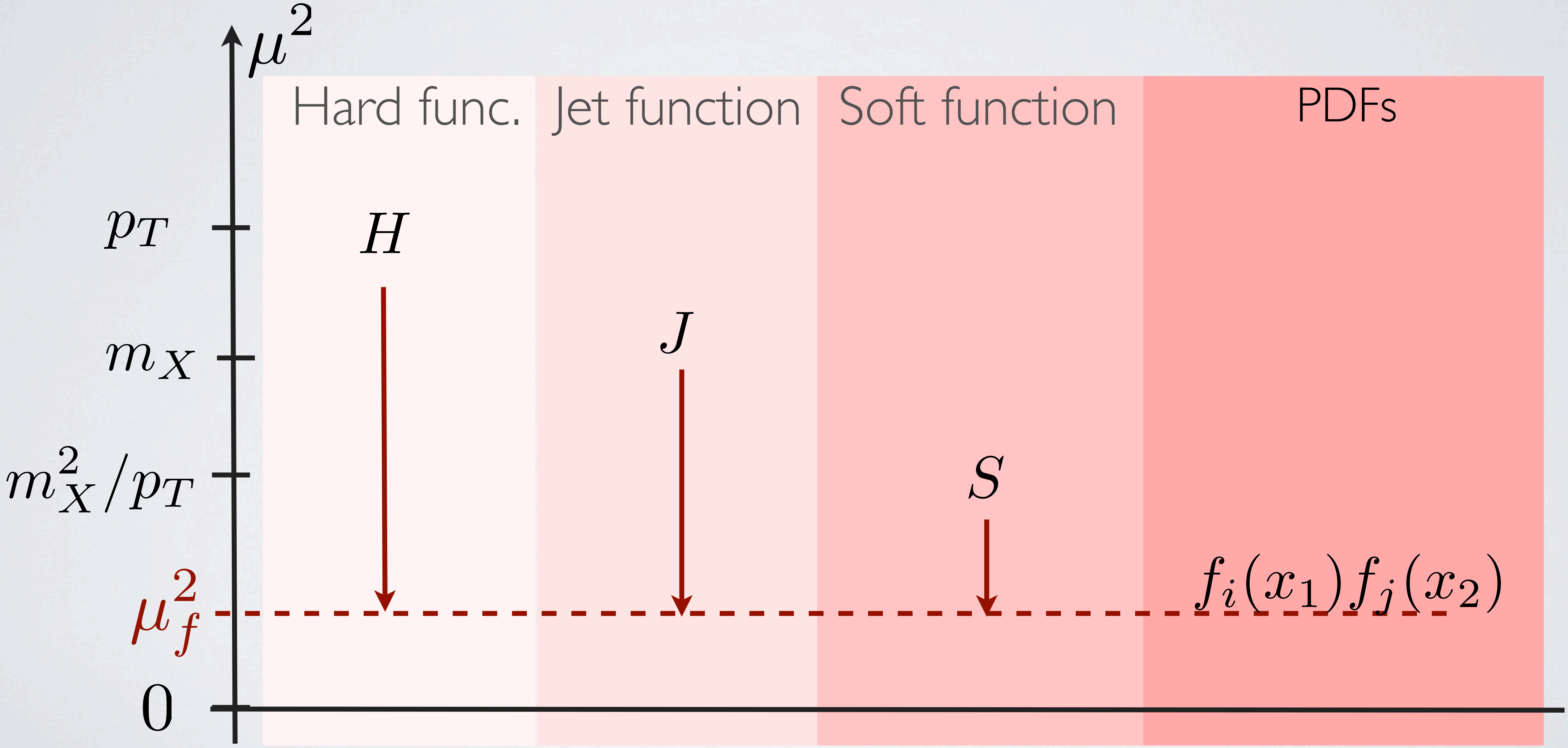



- Hard function is square of on-shell $qg \to q\gamma$ amplitude. Ellis et al. '83, Arnold and Reno '89
- Jet functions are quark and gluon propagators in light-cone gauge.
- Soft function is matrix element of Wilson lines $Y_i$ from $0 \ldots \infty$ along the beam and jet directions.

$$S_{\bar{q}q}(k_+) = \frac{1}{N_c} \sum_{X_s} \left| \left\langle X_s \left| \boldsymbol{T} \left[ Y_1^\dagger(0)\, Y_J(0) t^a\, Y_J^\dagger(0) Y_2(0) \right] \right| 0 \right\rangle \right|^2 (2\pi)\delta(n_J \cdot p_{X_s} - k_+)$$

# RESUMMATION BY RG EVOLUTION

- Evaluate each part at its characteristic scale, evolve to common scale:



# ANOMALOUS DIMENSIONS

- Have analytic solution for the RGs of H, J and S. TB and Neubert '06
- Using RG invariance and known results, we are able to extract all anomalous dimensions to *three loops*
  - Hard anomalous dimension $\Gamma_H$ from general result TB and Neubert '09 (see also Gardi and Magnea '09 + Dixon '09)
    - For *n*=3, the constraints determine $\Gamma_H$ uniquely.
  - Quark-jet function anomalous dimension $\Gamma_{J_q}$ known
  - Soft anom. dim. for qg channel is $\Gamma_{S_{qg}} = \Gamma_{H_{qg}} - \Gamma_{J_q}$
  - Soft anom dim. for qq channel is $\Gamma_{S_{\bar{q}q}} = \frac{2C_F - C_A}{C_A}\Gamma_{S_{qg}}$
  - Gluon-jet function anom. dim. is $\Gamma_{J_g} = \Gamma_{H_{\bar{q}q}} - \Gamma_{S_{\bar{q}q}}$

# ANOMALOUS DIMENSIONS

- Have analytic solution for the RGs of H[...] [...]ubert '06
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  - Gluon-jet function anom. dim. is $\Gamma_{J_g} = \Gamma_{H_{\bar{q}q}} - \Gamma_{S_{\bar{q}q}}$

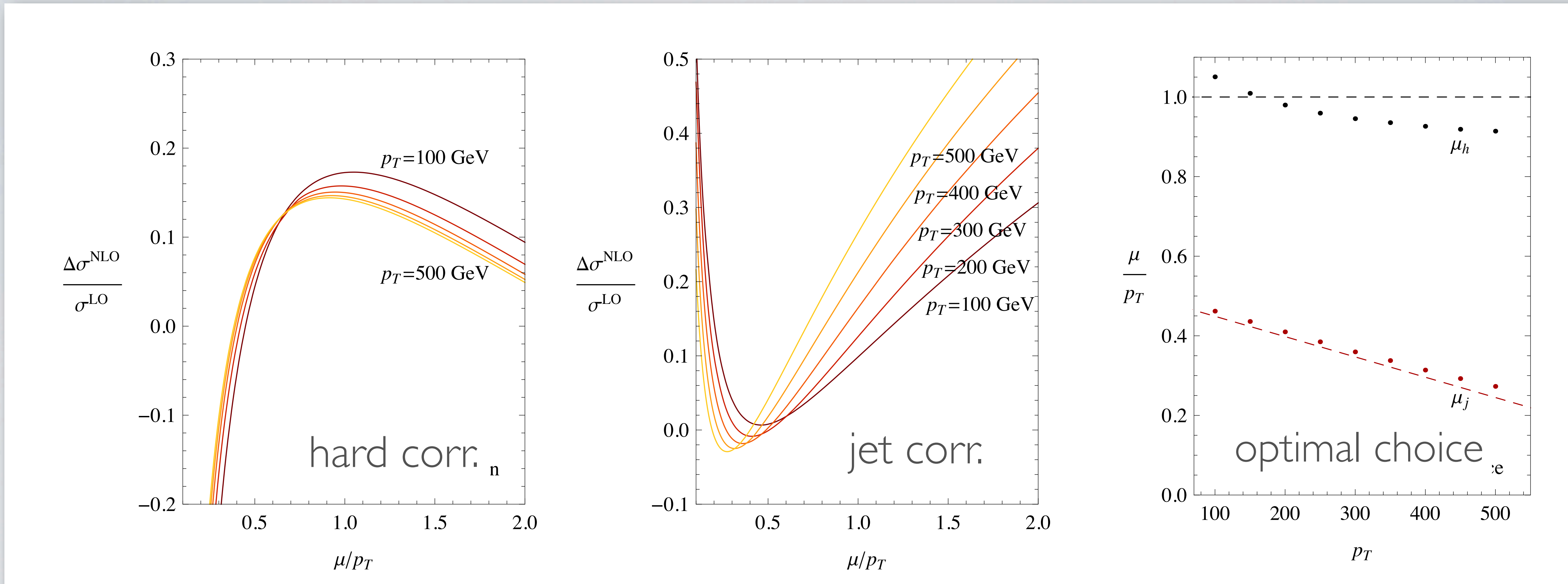
**Anomalous dimensions sufficient for NNNLL resummation!**

(but would need two-loop matching)

# SCALE CHOICE

- Natural choice for scale in hard function is $\mu_h \sim p_T$
- Choice of jet scale $\mu_j$ is more difficult, since *partonic* invariant mass varies $m_X = 0 \ldots M_X$ where the *hadronic* $M_X^2 = E_{\rm CM}^2(1 - p_T/p_T^{\rm max})$
  - For small $M_X$, *i.e. very* large $p_T$, $\mu_j \sim M_X$ is appropriate
  - Choice $\mu_j = m_X$ leads to Landau pole ambiguities; is implicit in trad. resummation method.
- Convolution with PDF dynamically enhances threshold region of low $m_{\rm X}$. TB Neubert '08
  - Would like to set $\mu_j$ to the average value of $m_{\rm X}$, but convolution with PDFs can only be done numerically.
  - Determine $\mu_j$ by looking at jet-function corrections as a function of $\mu_j$. Reasonable scale choice gives moderate corrections.

# SCALE CHOICE




- As a default, we choose

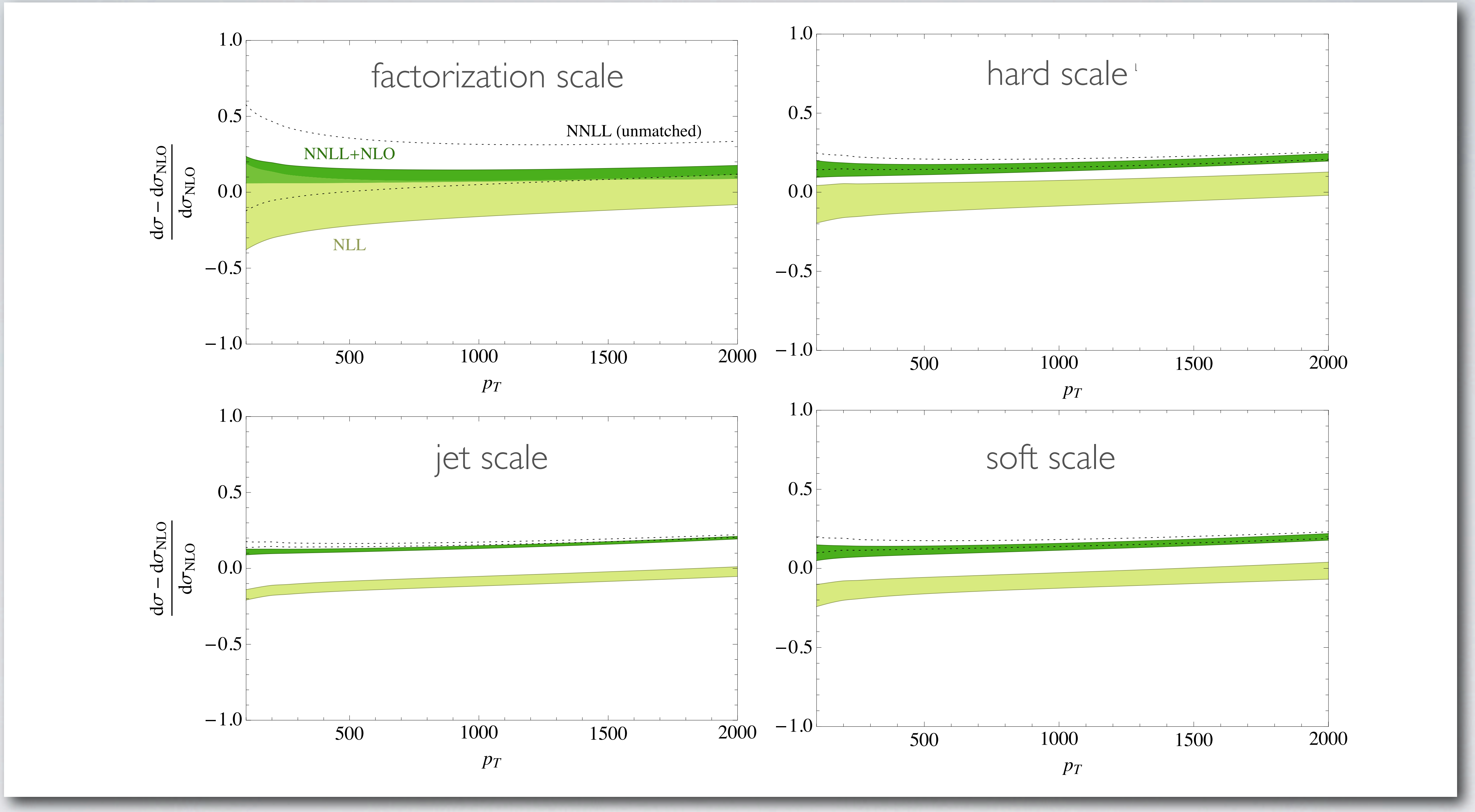
$$\mu_h = p_T\,,$$

$$\mu_j = \frac{p_T}{2}\left(1 - 2\frac{p_T}{E_{CM}}\right)\,,$$

$$\mu_s = \mu_j^2/\mu_h$$

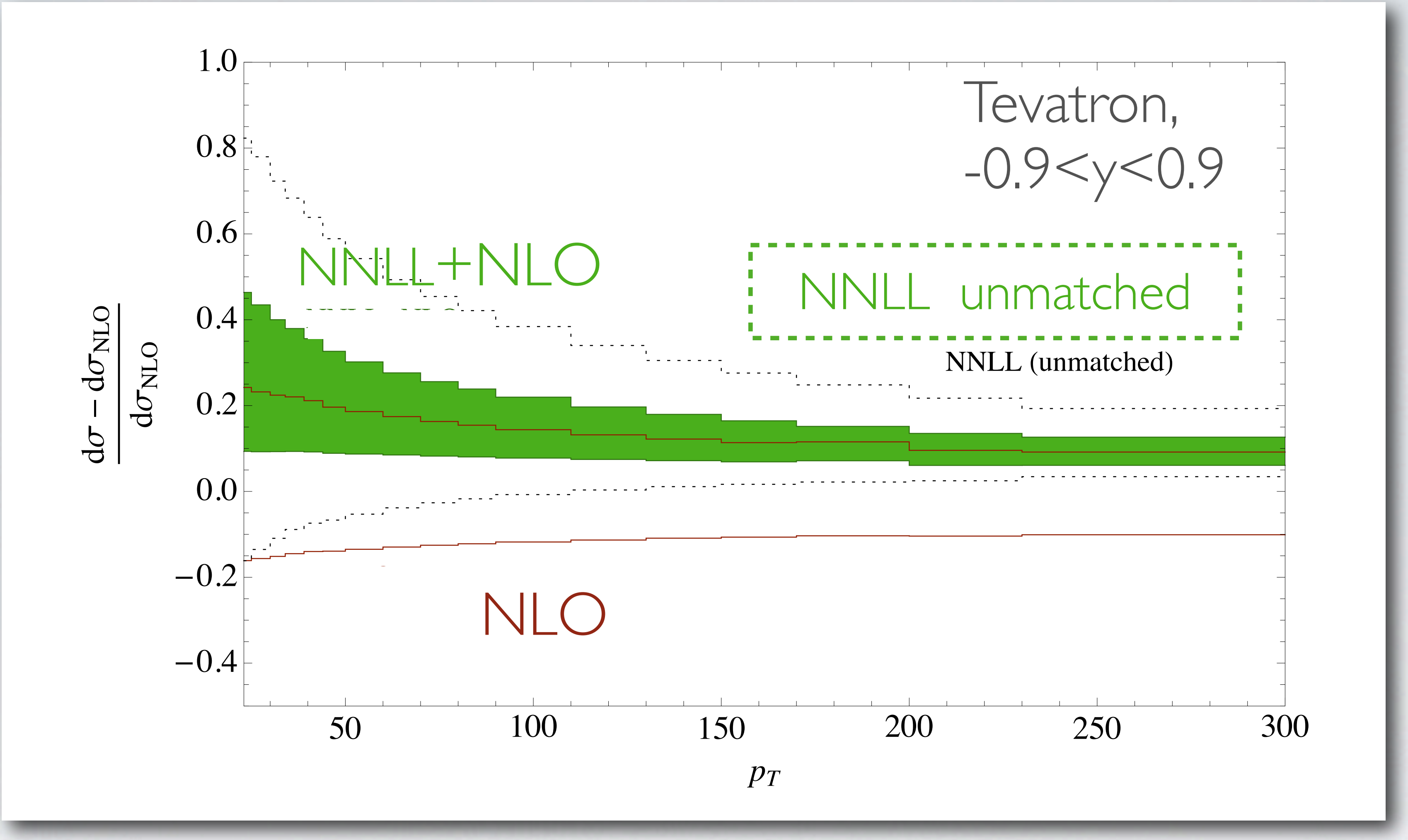
and vary by a factor two.

# SCALE VARIATIONS




- Matching scales variations are small, factorizations scale uncertainty dominates. Matching to NLO reduces factorization scale dep.

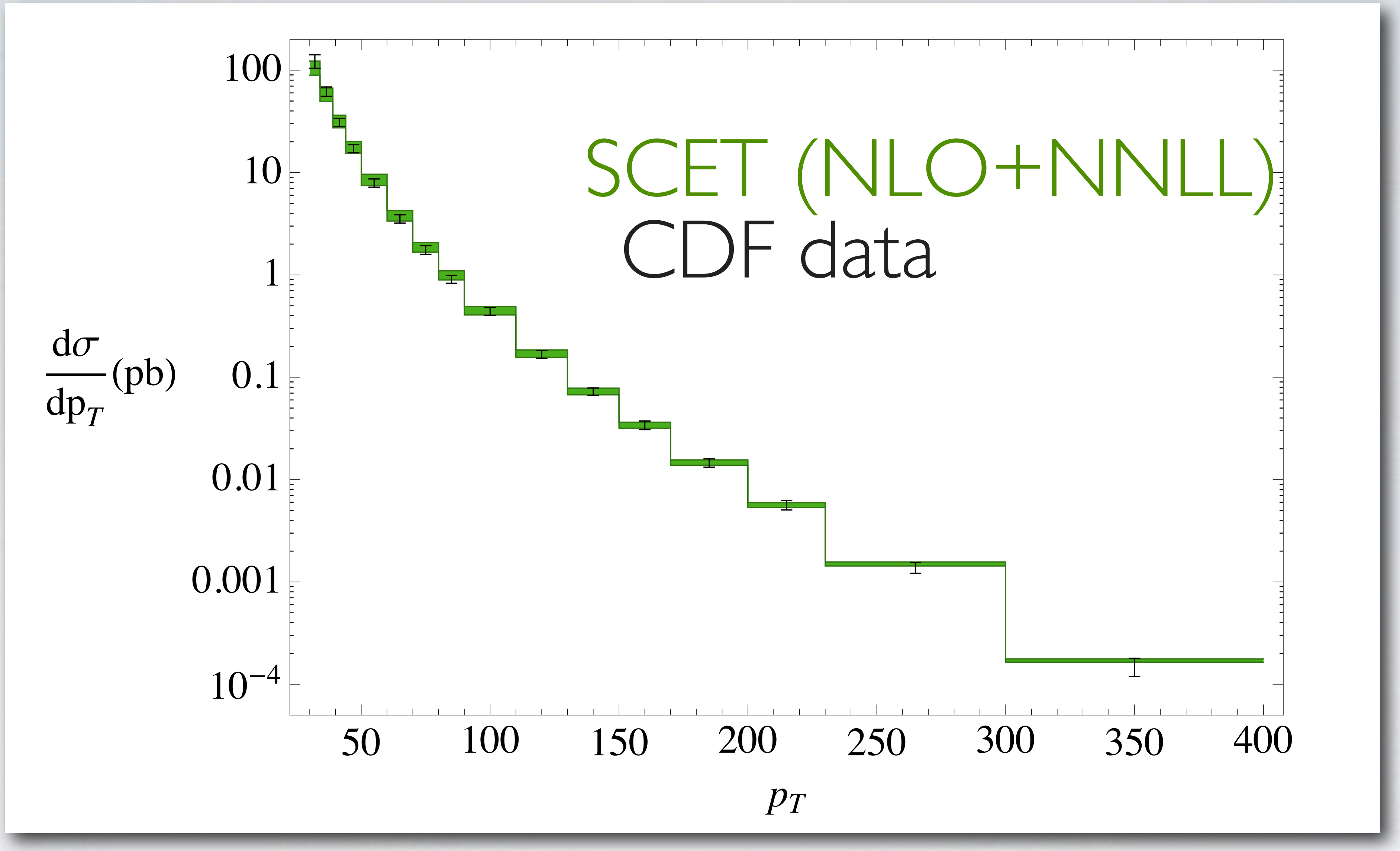
# MATCHING TO FIXED ORDER




- We match the NLO fixed order result in JETPHOX. This allows us to account for isolation cuts and fragmentation contributions.

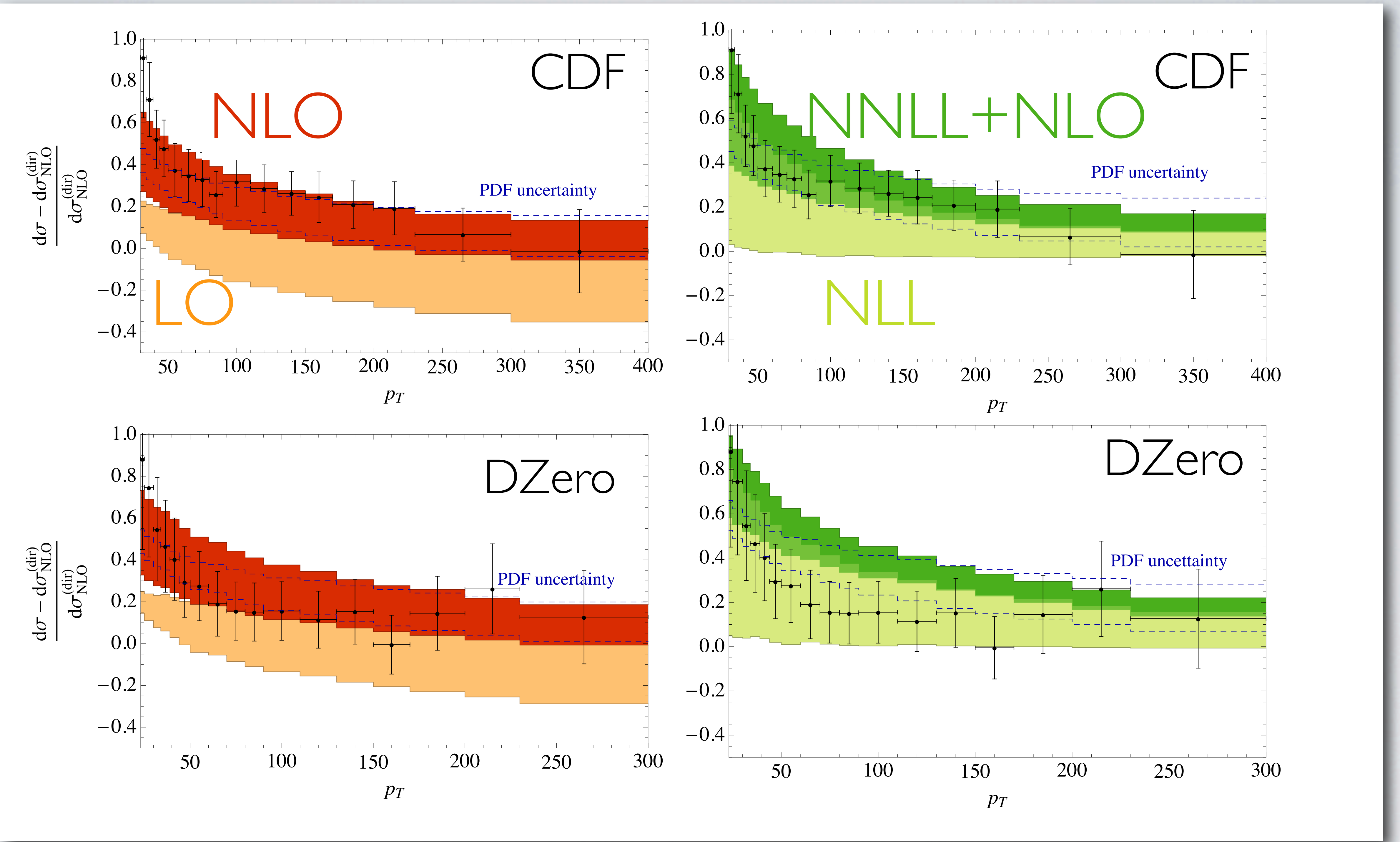
$$\left(\frac{d^2\sigma}{dv\,dw}\right)^{\text{matched}} = \left(\frac{d^2\sigma}{dv\,dw}\right)^{\text{NNLL}} - \left(\frac{d^2\sigma}{dv\,dw}\right)^{\text{NNLL}}_{\mu_h=\mu_j=\mu_s=\mu_f} + \left(\frac{d^2\sigma}{dv\,dw}\right)^{\text{NLO}}_{\mu_f} .$$

# CROSS SECTION AT THE TEVATRON



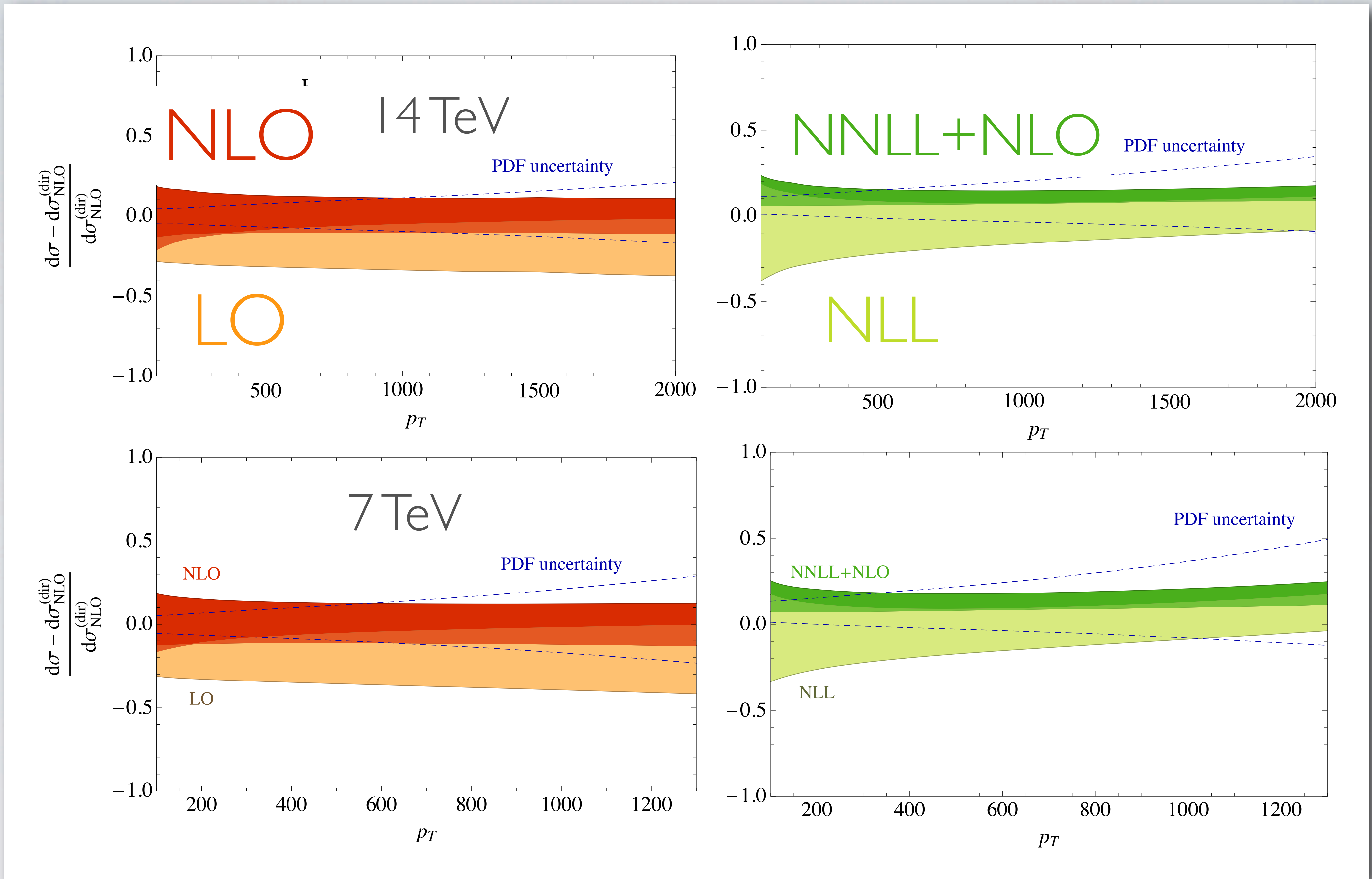

- Rapidly falling, so in the next slides I will plot $\dfrac{d\sigma - d\sigma^{(\mathrm{dir})}_{\mathrm{NLO}}}{d\sigma^{(\mathrm{dir})}_{\mathrm{NLO}}}$.
- $d\sigma^{(\mathrm{dir})}_{\mathrm{NLO}}$ is the *direct* photon production w/o isolation cuts.

# TEVATRON RESULTS



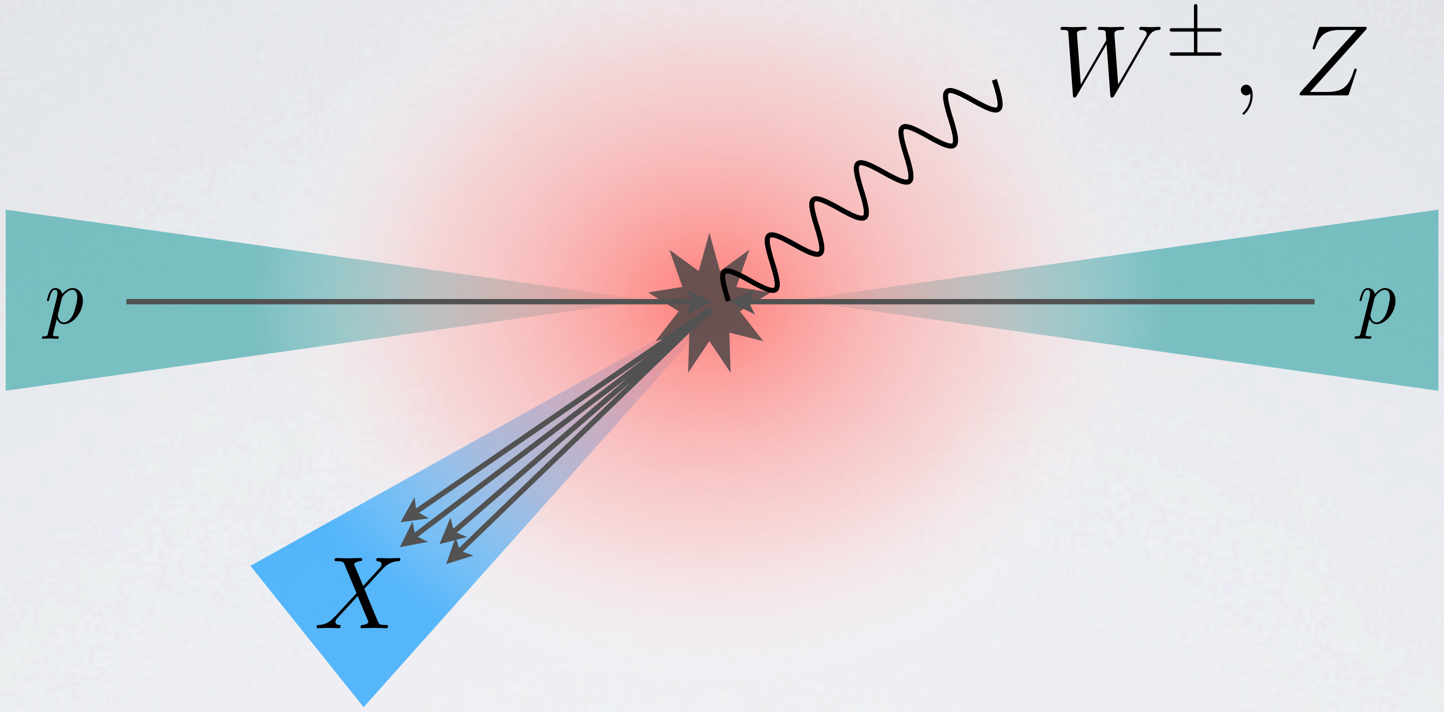

Fragmentation and isolation from JETPHOX. Additional hadronisation correction (a factor 0.91) as determined in CDF paper from MC studies.

# LHC RESULTS




- Direct contribution only: no fragmentation or isolation cuts.

# W AND Z PRODUCTION

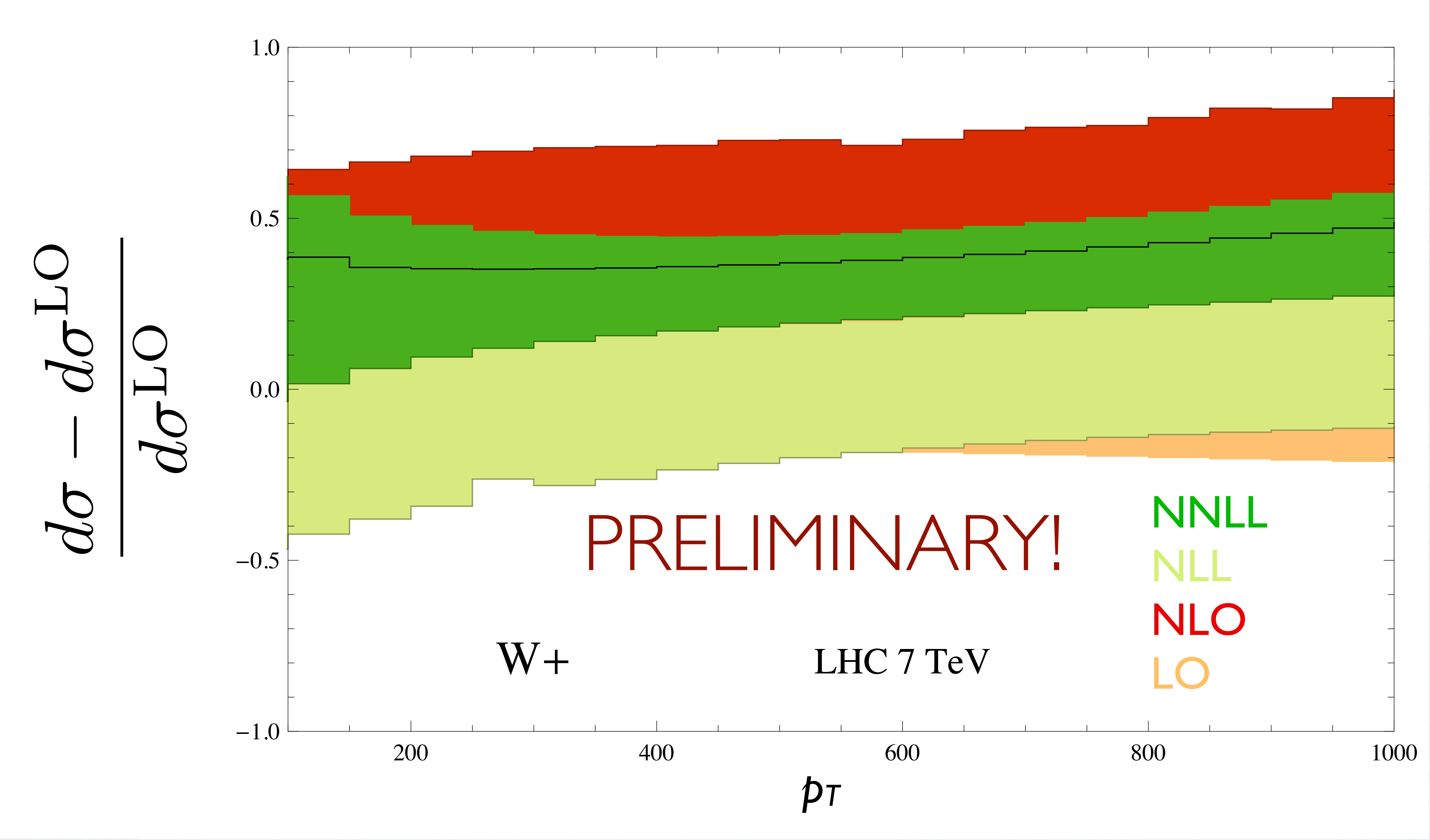



- Factorization theorem has exactly the same structure as in the photon case

$$\frac{d^2\sigma}{dy\,dp_T} = H \otimes J \otimes S \otimes f_1 \otimes f_2$$

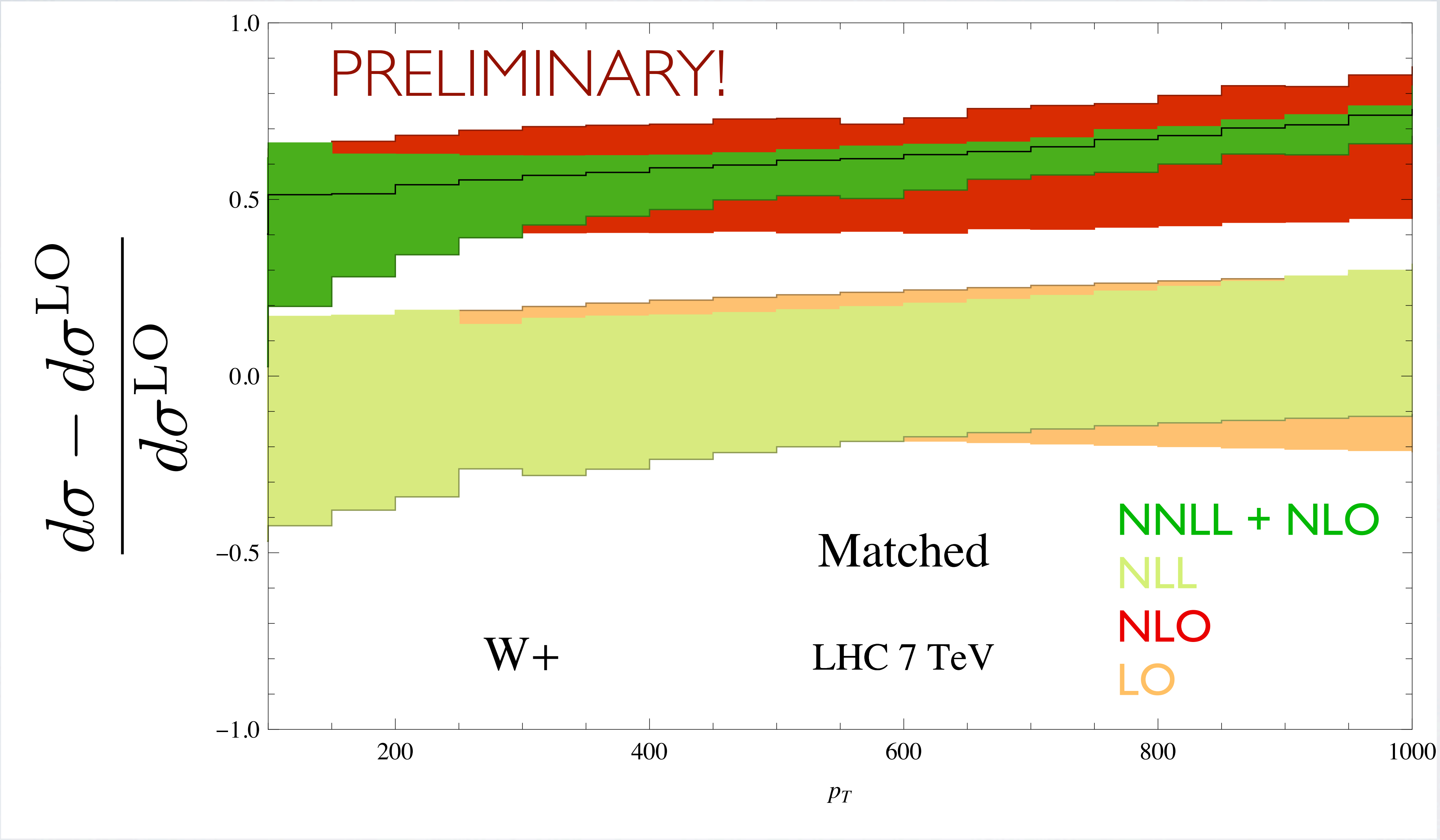
  - Same soft and jet function, but different hard function and kinematics.

# W AND Z PRODUCTION




- Use  MCFM for NLO
- All scales varied by a factor 2 around default

# W AND Z PRODUCTION




- NNLL+NLO has somewhat larger central value, reduced scale dependence.

# CONCLUSIONS

- A lot of progress during the past year towards the analysis of more complex collider observables in SCET
  - n-jet anomalous dimensions
    - completely known to NNLL
    - fulfills stringent all-order constraints
- First application involving three directions of large momentum flow
  - Photon production at large $p_T$ to NNLL
  - Computation of $W$ and $Z$ finished, phenomenological analysis in progress